DEPARTMENT OF HEALTH & HUMAN SERVICES

Public Health Service 93-62

Centers for Disease Control
National Institute for
Occupational Safety & Health
Robert A. Taft Laboratories
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Cincinnati OH 45226-1998

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January 11, 1994

Office of the Secretary
Federal Communications Commission
1919 M Street, N.W.
Washington, D.C. 20554

93-62

Dear Sir/Madam:

Staff of the National Institute for Occupational Safety and Health (NIOSH) have reviewed the FCC proposed rule on radiofrequency radiation exposure guidelines, published in the Federal Register on April 14, 1993 [58 FR 19393]. Our comments and supporting references are enclosed.

If you have any questions regarding our submission, please call me at (513) 533-8302.

Sincerely yours,

for Richard W. Niemeier, Ph.D.
Director
Division of Standards Development
and Technology Transfer

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NIOSH

Comments to FCC

COMMENTS OF THE
NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH
ON THE
FEDERAL COMMUNICATIONS COMMISSION
PROPOSED RULE ON
RADIOFREQUENCY RADIATION EXPOSURE GUIDELINES

47 CFR Part 1
ET Docket No. 93-62

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

1/11/93

The National Institute for Occupational Safety and Health (NIOSH) supports the Federal Communications Commission (FCC) in its effort to update the guidelines for evaluating the occupational and environmental effects of radiofrequency (RF) radiation.

The FCC proposes to modify its RF regulations by adopting new guidelines that have been developed by the Institute of Electrical and Electronic Engineers (IEEE) and published by the American National Standards Institute (ANSI). These guidelines have been designated IEEE C95.1-1991 by IEEE and ANSI/IEEE C95.1-1992 by ANSI. The frequency range covered by the FCC guidelines is from 3 kHz to 300 GHz.

While the maximum permissible exposure levels defined by ANSI/IEEE C95.1-1992 are similar to those defined by other related publications [NCRP 1986; WHO 1993], NIOSH is concerned about the lack of participation by experts with a public health perspective in the IEEE RF standards setting process. For example, epidemiology studies were categorically rejected as not useful in the process of setting the ANSI/IEEE C95.1-1992 limits. This lack of public health perspective creates a weakness in the ANSI/IEEE C95.1-1992 standard that should be acknowledged by the FCC in adopting these guidelines for regulating occupational and environmental exposures to RF radiation.

GENERAL COMMENTS

The provision of a two-tier standard based on "controlled" versus "uncontrolled" environments is problematic. The designation of controlled versus uncontrolled depends, in part, on the worker's knowledge of both the exposure level and the related health effects. It is extremely difficult to assess the level of a worker's "knowledge" and it is especially so when the standard does not provide any guidance on training programs or worker notification procedures. Therefore, the conservative public health approach would be to adopt only the more restrictive "uncontrolled environment" limits for all exposed workers and the general public.

The exposure levels that would be set by the standard are based on only one dominant mechanism -- adverse health effects caused by body heating. Nonthermal biological health effects have been reported in some studies and research continues in this area [NCRP 1986; WHO 1993]. The standard should note that other health effects may be associated with RF exposure and that exposure should be minimized to the extent possible.

In general, the standard provides minimal guidance on control measures, appropriate medical surveillance, training, or hazard communication.

SPECIFIC COMMENTS

Specific comments on various sections of the proposed standard to improve worker protection are as follows. The item number and the page number refer to the FCC notice of proposed rulemaking.

Page 6, Item 12

Regarding the definition of uncontrolled environment, which states that "there are no expectations that the exposure levels may exceed...", these "expectations" need to be based on some measurements or calculations of anticipated personal exposures. They should not be defined merely by presumption or past history, in view of the more restrictive guidelines (proposed) to be used from the ANSI/IEEE C95.1-1992.

Page 6, Item 13

The more "conservative approach" (i.e., one set of exposure limits) is appropriate, particularly with respect to general public exposure. Thus, if there is any question about exposure category (controlled versus uncontrolled), the uncontrolled criteria should be applied.

Page 8, Item 17

NIOSH agrees with the overall approach to hand-held portable devices. However, NIOSH questions whether it is possible or practical to ensure that "the radiating structure," which can include not only the whip antenna but in some cases the body of the cellular phone, is not within 2.5 cm of the body (e.g., head). If this spacing cannot be assured, exclusions based on radiated power should not be used. Thus, all cellular phones, with a "radiating structure" in the handset should require specific absorption rate (SAR) determinations to demonstrate compliance with the exclusion guidelines. Proof of such determinations should be submitted as part of the equipment authorization process.

Page 9, Item 20

The current categorical exclusions (i.e., for cellular phones and two-way radios) are not consistent with provisions of the ANSI/IEEE C95.1-1992 guidelines, and should not be carried over without new justification. The current FCC exclusions are based on the 1982 ANSI guidelines, and the FCC acknowledges that the 1992 ANSI/IEEE guidelines are more restrictive.

Page 10, Item 21

Categorical exclusions should be limited to situations where there is no possibility of excessive worker (as well as general public) exposure. However, it is not necessary to limit categorical exclusions to situations where field strengths will never be exceeded. If SAR or induced current maximum permissible exposures (MPEs) can be met (see ANSI/IEEE C95.1-1992, 4.2.1), field strengths can be exceeded. It is important to monitor the relative location of workers to the antenna/radiating structures.

If FCC intends to adopt the newer 1992 guidelines and carry over the old FCC categorical exclusions, an explanation should be provided of the basis for continuing use of the old exclusions that are no longer supported by the ANSI guidelines.

Certification of procedures, to preclude working near antennas, would be a protective approach. Careful determination of the worker's location, relative to antennas or metallic structures with RF current flow, is essential before meaningful SAR or current determinations can be made.

Evaluating exposure of workers within a few feet of a transmitting antenna must include determinations of SAR as well as induced and contact current in the body. Workers in these situations are receiving coupled exposures that cannot be evaluated using field strength measurements alone. It is critical to carefully determine where the workers are located, relative to the RF antenna or other metallic structure with current flow. The SAR and induced current determinations are explained in the ANSI/IEEE C95.1-1992 guidelines (see pages 13-14, 18-19 of these guidelines).

Page 10, Item 22

Induced body current could be measured for stations operating at and below 100 MHz. A frequency-tunable field intensity meter (e.g., Potomac® FIM-71) could be used to measure the induced current at and below 100 MHz. On the other hand, equipment and research are only available for the measurement of contact current up to 30 MHz. Stuchly et al. [1991] specified circuitry for a human equivalent impedance operable only up to 30 MHz and the Narda 8870 contact current meter only operates up to 30 MHz. A human equivalent impedance for 30 to 100 MHz should be developed, along with a practical contact current meter for 30 to 100 MHz. When developed, the frequency-tunable field strength meter could be used to determine the contact current flowing through this human equivalent impedance.

Regarding the split of the FM frequency band, induced current measurements should be required for up to 108 MHz, even though these frequencies are not included in the ANSI/IEEE C95.1-1992 guidelines. These frequencies could be measured with the same technology used at 100 MHz, if the instruments were properly calibrated.

Page 11, Item 24

The FCC has proposed using the more conservative approach (guidelines for "uncontrolled environment") when an area of uncertain definition exists. NIOSH agrees with this approach. If such a rationale were followed in this case, the lower limits of NCRP (see section 17.4 of NCRP [1986]) or WHO [1993] would be more conservative at the frequency ranges where such differences exist. However, these differences are not as important for the FCC-licensed sources of RF radiation as the inclusion of the induced current restrictions, which are not found in the NCRP guidelines.

Page 12, Item 25

The NCRP guidance states "If the carrier frequency is modulated at a depth of 50 percent or greater at frequencies between 3 and 100 Hz, the exposure criteria for the general population shall also apply to occupational exposures." There are data from in vitro and in vivo research noting effects under these conditions although the implications for risk to human health are not clear. It has been shown that modulation of this type (extremely low frequency, or ELF modulation) exists on amateur radio, microwave ovens, AM and FM radio, television, air traffic control radars, and LORAN. Further, RF sources have power supplies that are fed by 60 Hz power mains. The amount of ELF amplitude modulation (ripple) on the RF carrier depends on the quality or completeness of filtering on the power supplies. Thus, it follows that many, if not most signals from RF sources will have measurable ELF amplitude modulation. Before making ELF amplitude modulation restrictions, it may be useful to determine the depth or amount of ELF amplitude modulation in other common RF sources and the ease of making these measurements. The cost and reliability of such measurements is not clear.

Page 13, Item 27

The Commission should require more complete documentation or evidence from applicants who claim compliance with environmental RF radiation guidelines. The documentation should include laboratory data with calculations or measurements to support the claim. The data should be provided in a form suitable for scientific review, with sufficient detail to critique the method used to establish that data.

Pages 13-14, Item 28

The ANSI/IEEE C95.3-1992 guidelines for measurement procedures are appropriate for showing compliance.

Page 14, Item 29

Notes on specific types of equipment have been made elsewhere in these comments. In addition, the measurement guidelines set forth in IEEE C95.3-1991 are also relevant here. NIOSH was a participant in the development of C95.3 recommendations.

REFERENCES

NCRP [1986]. Biological effects and exposure criteria for radiofrequency electromagnetic fields. Bethesda, MD: National Council on Radiation Protection and Measurements, NCRP Report No. 86.

Stuchly MA, Kozlowski JA, Symons S, Lecuyer DW [1991]. Measurements of contact currents in radiofrequency fields. Health Physics 60(4):547-557.

WHO [1993]. Electromagnetic fields (300 Hz to 300 GHz). Geneva, Switzerland: World Health Organization, Environmental Health Criteria 137.

NCRP REPORT No. 86

BIOLOGICAL EFFECTS AND EXPOSURE CRITERIA FOR RADIOFREQUENCY ELECTROMAGNETIC FIELDS

NCRP

National Council on Radiation Protection and Measurements

W. G[illegible] Lotz, Ph.D.

NCRP REPORT No. 86

Biological Effects and Exposure Criteria for Radiofrequency Electromagnetic Fields

Recommendations of the
NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS

Issued April 2, 1986

National Council on Radiation Protection and Measurements
7910 WOODMONT AVENUE / BETHESDA, MD. 20814

Library of Congress Cataloging-in-Publication Data

National Council on Radiation Protection and Measurements.

Biological effects and exposure criteria for radiofrequency electromagnetic fields.

(NCRP) report ; no. 86)
"Issued April 15, 1986.
Bibliography: p.
Includes index.
1. Electromagnetism—Physiological effect. 2. Electromagnetism—Toxicology. 3. Radio waves—Physiological effect. 4. Radio waves—Toxicology. I. Title. II. Series.

QP82.2.E43N38 1986   612′.01442   86-2451
ISBN 0-913392-80-4

Contents

Health Physics Vol. 60, No. 4 (April), pp. 547–557, 1991
Printed in the U.S.A.

0017-9078/91 $3.00 + .00

● *Paper*

MEASUREMENTS OF CONTACT CURRENTS IN RADIOFREQUENCY FIELDS

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Abstract—**Radiofrequency electromagnetic fields can affect human health not only by direct interactions but indirectly through induction of charges on isolated or poorly grounded conductive (metallic) objects located in these fields. A person who touches such an object may perceive a tingling or prickling sensation or heat, or experience pain or electric shock. For sufficiently large objects, these phenomena can occur at field strengths that are relatively low and below the health protection limits based on direct interactions. We describe a method and circuitry developed to evaluate steady-state contact currents that may flow through a person touching conductive objects and give a summary of experimental tests performed. The method is simple and viable for field tests aimed at preventing pain, shock, and burn hazards in radiofrequency electromagnetic fields except those related to spark discharges. The method is applicable up to about 30 MHz.**

INTRODUCTION

RADIOFREQUENCY (RF) electromagnetic fields may pose a potential health hazard at intensity levels that are below the levels recommended in many standards and which have been based on direct interactions of the fields with human beings. This indirect potential health hazard is due to RF charges induced on conductive (metallic) ungrounded or poorly grounded objects, such as cars, buses, trucks, cranes, fences, located in the RF field. When a person comes in contact with such objects, two phenomena may occur. Before the person touches the object, a spark discharge may take place if the charge accumulated on the object is sufficiently large. After touching the object, the steady-state discharge current flows through the body, with the highest current density most likely in the contact location. Depending on the current density, the steady-state contact current for low current densities is perceived as a tingling/prickling sensation below about 100 kHz and as warmth above 100 kHz. For higher current densities it is painful, and for a sufficiently high current, burns or more serious injury can occur. This problem has been recognized previously (Gandhi et al. 1985; Guy 1985) and has also recently found reflection in proposed safety standards, e.g., the American National Standards Institute 1990 revision‡ and the Canadian proposal (Stuchly 1987).

Threshold current values for perception and pain have been measured for both sexes and estimated for children at frequencies from 10 kHz to 30 MHz (Chatterjee et al. 1986; Gandhi 1987). The human body impedance has also been measured and equivalent circuits developed (Kanai et al. 1984; Gandhi et al. 1985; Richman 1985).

Since it is rather unreasonable to employ human volunteers to evaluate whether perception or pain are experienced when touching various objects in RF fields, a measurement method has to be developed that electrically simulates the conditions experienced by a person subjected to contact currents to ground from a conducting object. A measurement method of steady-state currents developed for this purpose, which utilizes the currently available information on the perception and pain thresholds and on the equivalent impedance of the human body, is described and results of laboratory and field tests are given.

MATERIALS AND METHODS

Selecting test conditions

In developing protection standards from potential hazards from contact currents, one may want to protect humans from perception or pain. In the proposed Canadian recommendations, it was decided to establish limits below the perception threshold for children for the general population and below the threshold of pain for occupational exposures (Stuchly 1987). As shown by earlier measurements, these thresholds depend on the type of contact. Perception and pain occur at lower currents for finger contact than for grasping (hand) contact (Chatterjee et al. 1986; Gandhi 1987). However, since the impedance of the human body also depends on the type of contact (Kanai et al. 1984; Gandhi et al. 1985), it is

(*Manuscript received* 15 *November* 1989; *revised manuscript received* 24 *September* 1990, *accepted* 15 *October* 1990)

‡ Personal communication (1990) with O.P. Gandhi, Department of Electrical Engineering, University of Utah, Salt Lake City, UT 84112.

not apparent which thresholds and corresponding equivalent impedance should be selected for testing.

We have rationalized that the conditions corresponding to the lowest value of the product of the threshold current, I, and the modulus of the equivalent impedance $|\hat{Z}|$ should be selected. These conditions correspond to the lowest potential induced on the object resulting in perception or pain, and to the lowest strength of the RF electric field.

The calculation for perception based on the data given by Gandhi (1987) and the equivalent impedance for wet contact and a barefooted person (the lowest impedance) showed that the products $I|\hat{Z}|$ varied from nearly the same value at 10 kHz for the finger and grasping contacts to values about 2.5 times lower for the finger contact than from the grasp contact at frequencies above 100 kHz. Therefore, finger contact was selected for further considerations.

From graphs on perception and pain (Gandhi 1987), the following threshold values were selected for the general population:

$$I \leq 150f, \quad \text{for} \quad f = 0.01 - 0.1 \text{ MHz}, \qquad (1)$$

where I is the threshold current in mA and f is the frequency in MHz, and

$$I \leq 15, \quad \text{for} \quad f = 0.1 - 100 \text{ MHz}. \qquad (2)$$

For the workers:

$$I \leq 400f, \quad \text{for} \quad f = 0.01 - 0.1 \text{ MHz} \qquad (3)$$

and

$$I \leq 40, \quad \text{for} \quad f = 0.1 - 100 \text{ MHz}. \qquad (4)$$

It may be noted that these values for frequencies below 100 kHz are different from those proposed earlier (Stuchly 1987). These thresholds are somewhat lower giving a greater margin of safety. In addition, their formulation is mathematically simpler.

Based on measurements at frequencies from 10 kHz to 3 MHz of a relatively large number of male and female volunteers, and measurements above 3 MHz of a few persons, a fairly complex equivalent circuit for the human body impedance was proposed by Gandhi and his associates (Gandhi et al. 1985; Kanai et al. 1984). This model provides several options, namely: type of contact (finger or grasping); condition of the contact surface (wet or dry); and shoe wear (barefoot or electrical safety shoes).

For our tests, the finger contact model applies. Furthermore, as explained earlier, we selected to test under the worst-case conditions, i.e., for the smallest modulus of the impedance. This leads to the selection of the wet contact surface and barefoot condition. The simplified model derived from Gandhi's model (Gandhi et al. 1985) is shown in Fig. 1. This model is representative of an average man. For an average woman, the modulus of the total and partial impedances is higher than for the average man. The use of the model representing the average man provides an additional safety factor because of the lower value of $|\hat{Z}|$. This equivalent circuit comprises a resistance R_s, a component of skin impedance, which is frequency-dependent. From the practical point of view, this is cumbersome. We examined the effect of neglecting R_s on the total equivalent impedance (modulus). The results are shown in Table 1. It can be seen that the differences are small, and the impedance is lower when R_s is removed.

Since Gandhi's model was based on a limited number of measurements at frequencies above 3 MHz, we also considered another model developed for electrostatic discharge (ESD) and applicable to higher frequencies (Richman 1985). This model is comparable to the dry contact surface and safety shoes model of Gandhi. Richman's model is shown in Fig. 2, and a comparison of impedances of the two models at frequencies from 1 to 100 MHz is given in Table 2. The differences are not greater than 23%.

Figure 3 shows the final circuit selected for testing. In some occupational situations, the limits imposed by eqns (3) and (4) may be too restrictive. In practice, some workers wear electrical safety shoes. Table 3 compares the impedances of the model for two options, namely barefoot and with safety shoes. The equivalent circuit for the impedance of a person wearing electrical safety shoes is shown in Fig. 4. From Table 3, it is apparent that electrical safety shoes significantly change the impedance only below 1 MHz, and therefore, the circuit shown in Fig. 4 needs to be used only at frequencies from 10 kHz to about 1 MHz.

Test circuit measurements

Impedances of test circuits and foot-current sensors were measured using an automatic network analyzer.[§]

To evaluate the test circuit for the human body impedance before it is used outside the laboratory, additional laboratory tests were performed. The current through the finger of a person touching an RF-energized electrode was compared with the current through the feet. A diagram of the experimental arrangement is shown in Fig. 5. The following instruments were used: RF generators—Wavetek[||] model 116 at frequencies of 10 kHz to 1 MHz, Hewlett-Packard[¶] model 8116A at frequencies of 0.1 to 50 MHz, and Wavetek[||] model 3000 at frequencies of 1–100 MHz; RF voltmeter—Rohde and Schwarz[#] model URV5; current probe—ETN[**] model 94111-2.

The electrode consisted of a square surface of a 1.44-cm^2 thin copper area soldered to the center conductor of

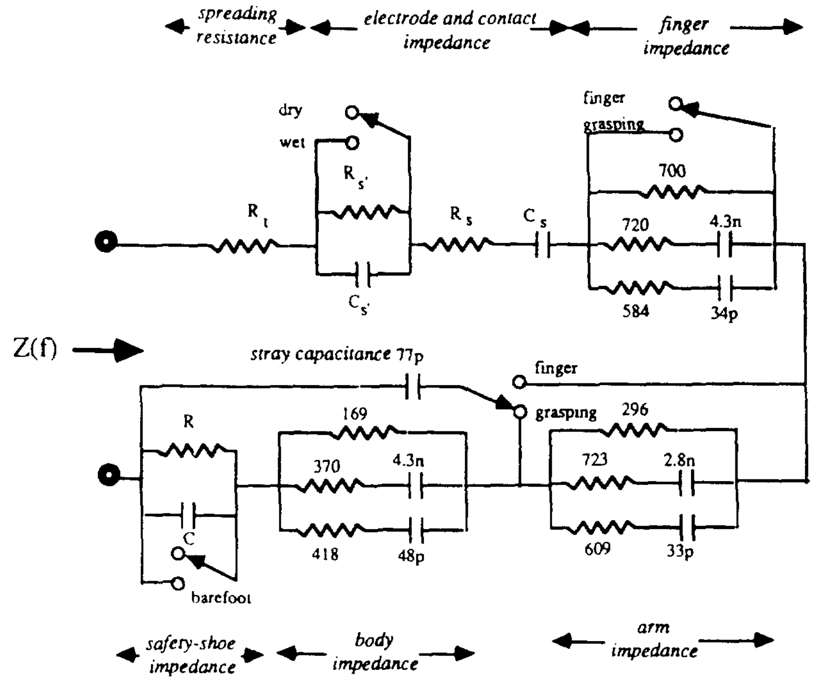
§ Model 3577, Hewlett-Packard Inc., P.O. Box 10301, Palo Alto, CA 94303-0890.

|| Wavetek, San Diego, Inc., 9045 Balboa Ave., San Diego, CA 92123.

¶ Hewlett-Packard Inc., P.O. Box 10301, Palo Alto, CA 94303-0890.

\# Rohde and Schwarz GMBH & Co. kG, Mühldorfstotrasse 15, D-8000 München 80, Federal Republic of Germany.

** Eaton Corporation, Electronic Instruments Division, Los Angeles, CA 30066.



$R_t = 378/\surd a$ $\qquad$ $C_s' = 30a$ (nF)

$R_s' = 37.5 \cdot 10^3/\surd a$ $\qquad$ $C_s = 28\ \surd a$ (nF)

$R_s = 2.45 \cdot 10^3/af$ $\qquad$ $C = 70$ pF

$R = 0.68 \cdot 10^{12}/f^{0.67}$

Resistances in (Ω), capacitances in (F), a in (cm), f in (kHz).

Fig. 1. Simplified model of the human body impedance based on Gandhi's model (Gandhi et al. 1985).

an N connector of a 50 Ω coaxial cable 0.3 m in length and terminated by a BNC connector. The outer connector (ground) is only connected to ground on the RF generator side. Our experience indicates that a longer cable, additional connection to ground by a long wire, or any appreciable length of an exposed center connector produce significant artifacts at frequencies greater than about 10 MHz and can cause serious errors in measurements. These effects include appreciable stray fields in the space around

Table 1. Modulus of the human body impedance for finger contact, barefeet, with and without R_s.

Frequency (MHz)	$\lvert Z\rvert$ (Ω) With R_s	$\lvert Z\rvert$ (Ω) Without R_s	$\Delta\lvert Z\rvert:\lvert Z\rvert$ (%)
0.01	1712	1554	−9.2
0.1	1087	1070	−1.6
1.0	981	979	−0.2
10	675	675	0
100	539	539	0

the electrode extending a few meters away instead of the fields being confined to about 0.01 m. The effect of stray field is easily detectable as changes in voltage due to the presence and motion of objects or persons. The stray fields then couple directly to the person, and consequently, the RF current through the feet consists of the field-induced current and the conduction current through the finger in contact with the electrode. Other undesirable effects are the inductance of an additional grounding wire that may resonate with the capacitances of the electrode and cable. The long cable through its capacitance and inductance may also affect the RF generator. All the spurious responses can be monitored by substituting a known resistor connected to ground in place of the person and measuring the currents and voltages as shown in Fig. 5.

The current probe has a 3-dB flat frequency response from 1 MHz to 1 GHz. In order to extend its use to lower frequencies, a simple calibration was performed using the same RF generator and RF voltmeter and a resistor of a known resistance. The current probe response was compared with the current in this test circuit measured as a voltage drop over the known resistance.

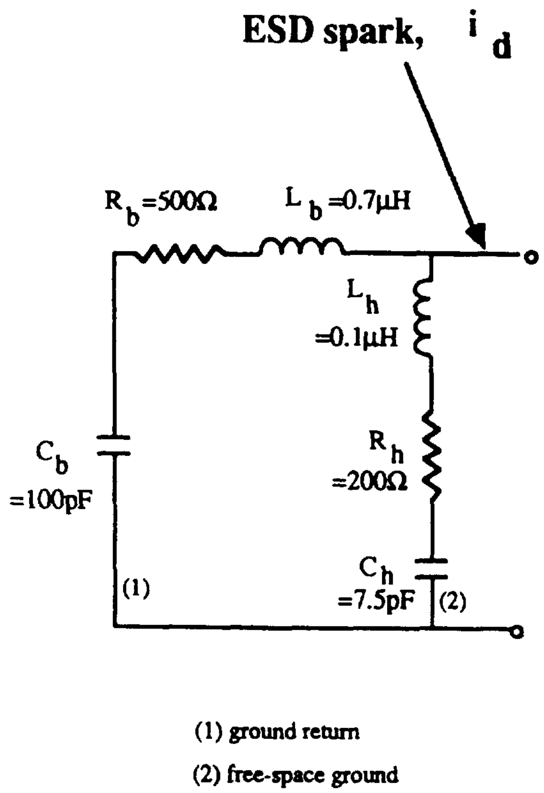


Fig. 2. Richman model of the human body impedance (Richman 1985).

Foot-current sensors

A foot-current sensor consists of two parallel copper plates separated by a certain distance. A 10 Ω resistor is positioned between the plates for measuring the RF voltage due to the contact current flow. Similar sensors were previously used at frequencies below 3 MHz by Gandhi (1987), Gandhi et al. (1985), and Guy (1985). The foot-current sensor is placed on a 1-m^2 metal plate connected to ground. This type of sensor has to be carefully constructed to operate properly at frequencies above 10 MHz. The sensor-equivalent circuit consists of a capacitor in parallel with a resistor (10 Ω). Capacitance of the capacitor depends on the surface area of the copper plates, the distance between them, and the dielectric constant of the material between them. Obvious requirements are that the sensor capacitance and the resistor inductance should be low so that their equivalent series reactances at the highest frequency are small compared with the 10 Ω resistance. Furthermore, the RF voltage has to be measured right at the connector attached to the sensor as even a short cable (e.g., 0.3 m) is capable of introducing a large measurement error. This is why an RF voltmeter must be used rather than an oscilloscope to measure this voltage.

To illustrate this point, we will describe how small differences in construction of the sensor affect its performance. Two sensors have been built and tested. These sensors consist of square copper plates of 0.3 m × 0.3 m, separated by a styrofoam layer 0.1 m thick, and a 10 Ω low-inductance carbon resistor connected between the plates to a standard BNC connector. Simplified sketches of the sensors are shown in Fig. 6. In both sensors, the BNC connector is mounted on a copper plate attached at a right angle to the ground (lower) plate of the sensor. In the first model, designated here as "A," one end of the resistor was soldered to the ground of the BNC connector and the other end to the "hot" end of the BNC connector and through a section of shielding about 5 mm wide and 0.08 m long; it was connected (soldered) to the upper plate of the sensor. In the other sensor, called "B," a copper strip 0.02 m wide was attached at a right angle to the upper plate of the sensor, and a chip 10 Ω resistor was soldered between this copper strip and the center conductor of a BNC connector, which was also attached to the lower (ground) plate.

RESULTS

Foot-current sensors

Figures 7 and 8 show the impedance of the foot-current sensors A and B, respectively. For sensor A, a considerable inductive component can be seen. For instance, at 50 MHz it represents a reactance of 15 Ω compared with a resistance of 10.7 Ω. Furthermore, a few low *Q* resonances can be seen above 50 MHz. One the other hand, in sensor B the inductance has been greatly reduced and the reactance corresponds to the capacitance between the plates and stray capacitance. However, this capacitance is reasonably small, and at, for instance, 60 MHz the series reactance representing the parallel capacitance is 0.25 Ω compared with the resistance of 10.7 Ω; even at 100 MHz, the reactance is 3 Ω and the resistance 12 Ω. Figure 9 illustrates the sensor impedance when a person (1.62-m, 50-kg female) stands on the upper plate barefoot without contact with any object. The impedance is affected; however, the changes are small. The total variations in resistance are within less than 1.5 Ω, and the maximum reactance (at 100 MHz) is 3 Ω (capacitive). The changes of the impedance as a function of frequency have to be considered in evaluating the accuracy of foot-current measurements using the foot-current sensor described. It is estimated that the accuracy is approximately ±10%.

Test circuit impedance

Circuits shown in Figs. 3 and 4 were built using low-inductance resistors and high-frequency capacitors to en-

Table 2. Modulus of the human body impedance from the Gandhi model (G) and the Richman model (R) (dry finger contact, a = 1.44 cm^2, safety shoes).

Frequency (MHz)	|Z| (Ω) G	|Z| (Ω) R	Δ|Z|:|Z| (%)
1	1354	1664	−23
3	829	720	13
10	632	513	19
30	559	506	9
100	539	655	−23

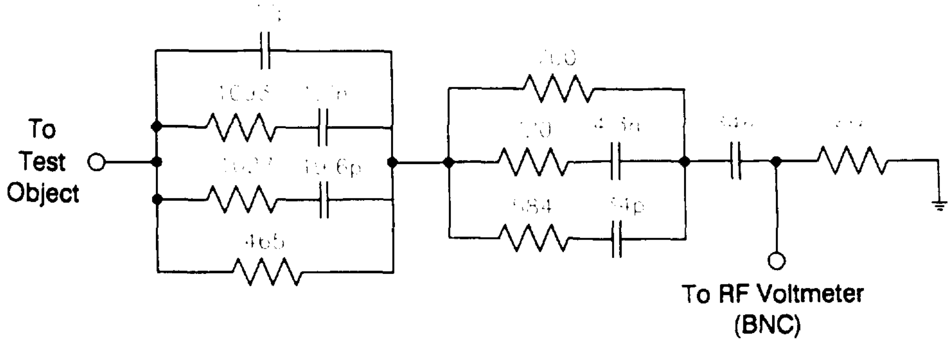


Fig. 3. Circuit for testing contact currents with barefeet. Frequency range, 0.01–100 MHz. All resistors in Ω, capacitors in F with the prefixes shown.

sure operation up to 100 MHz. The elements are mounted on a printed board, and special care has been exercised in the layout and connections to minimize spurious inductances and stray capacitances. Lead lengths for all components have been kept as small as possible, and proper separation between components has been used. The circuit impedance as a function of frequency is shown in Fig. 10. A few calculated values (circles) are given for comparison.

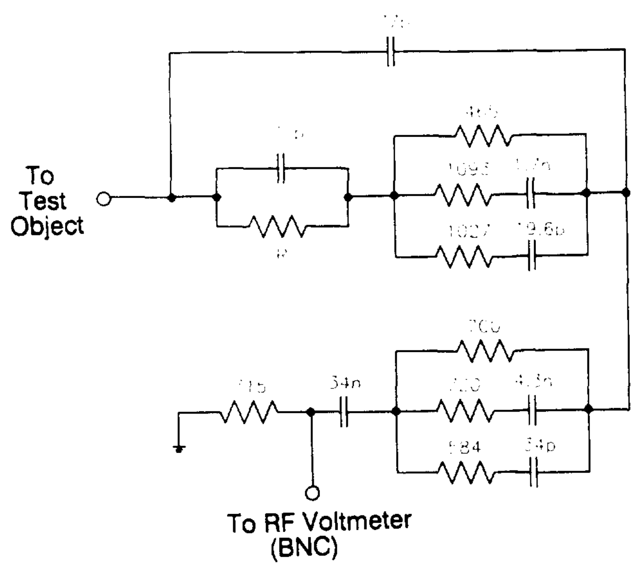
Additionally, RF voltages on the input and output terminals of the test circuit, representing human body impedance connected between the electrode and the ground plane, were measured as a function of frequency in the experimental arrangement shown in Fig. 5. Current through the circuit was calculated by dividing the measured voltage at the output terminal by the modulus of the output impedance. Then, the test circuit impedance (modulus) was calculated as a ratio of the input voltage to the current. These values were compared with those measured by the network analyzer and shown in Fig. 10. An agreement within ±10% was obtained.

Comparison of foot and finger currents

A test was performed using the experimental arrangement in Fig. 5 to evaluate the relationship between the foot current and the finger current. The difference between them was anticipated on the basis of the equivalent impedance of the human body, as shown in Fig. 1. It can be noticed that there is a 77-pF capacitor representing stray capacitance. When the foot current is measured using the sensor described, the current flowing through the finger is divided between the current flowing through the stray capacitance as displacement current and the current flowing through the other branch of the equivalent circuit or in reality through the person's body and the feet to the foot-current sensor (to the upper plate and then to ground). The ratio of the currents through the finger and the feet is shown in Fig. 11. These results can be reasonably attributed to the stray capacitance that varies from the equivalent of about 20 kΩ at 100 kHz to 210 Ω at 10 MHz and 21 Ω at 100 MHz. These values can be compared with the modulus of the body impedance (shown in Table 1). An exact comparison is not possible because of the difference in the dimensions of the foot-current sensor plates (approximately 0.1 m^2) and normally infinite ground.

Table 3. Modulus of the human body impedance for finger contact barefoot (B) and with electrical safety shoes (S).

Frequency (MHz)	|Z| (Ω) B	|Z| (Ω) S	Δ|Z|:|Z| (%)
0.01	1,554	109,000	6,900
0.1	1,070	11,000	928
1.0	979	1,350	38
10	675	683	—
100	539	539	—



$$R = 1.47 \cdot 10^7 / f^{0.67}$$

f in kHz

Fig. 4. Circuit for testing contact currents with electrical safety shoes. Frequency range, 0.01–1 MHz. All resistors in Ω, capacitors in F with the prefixes shown.

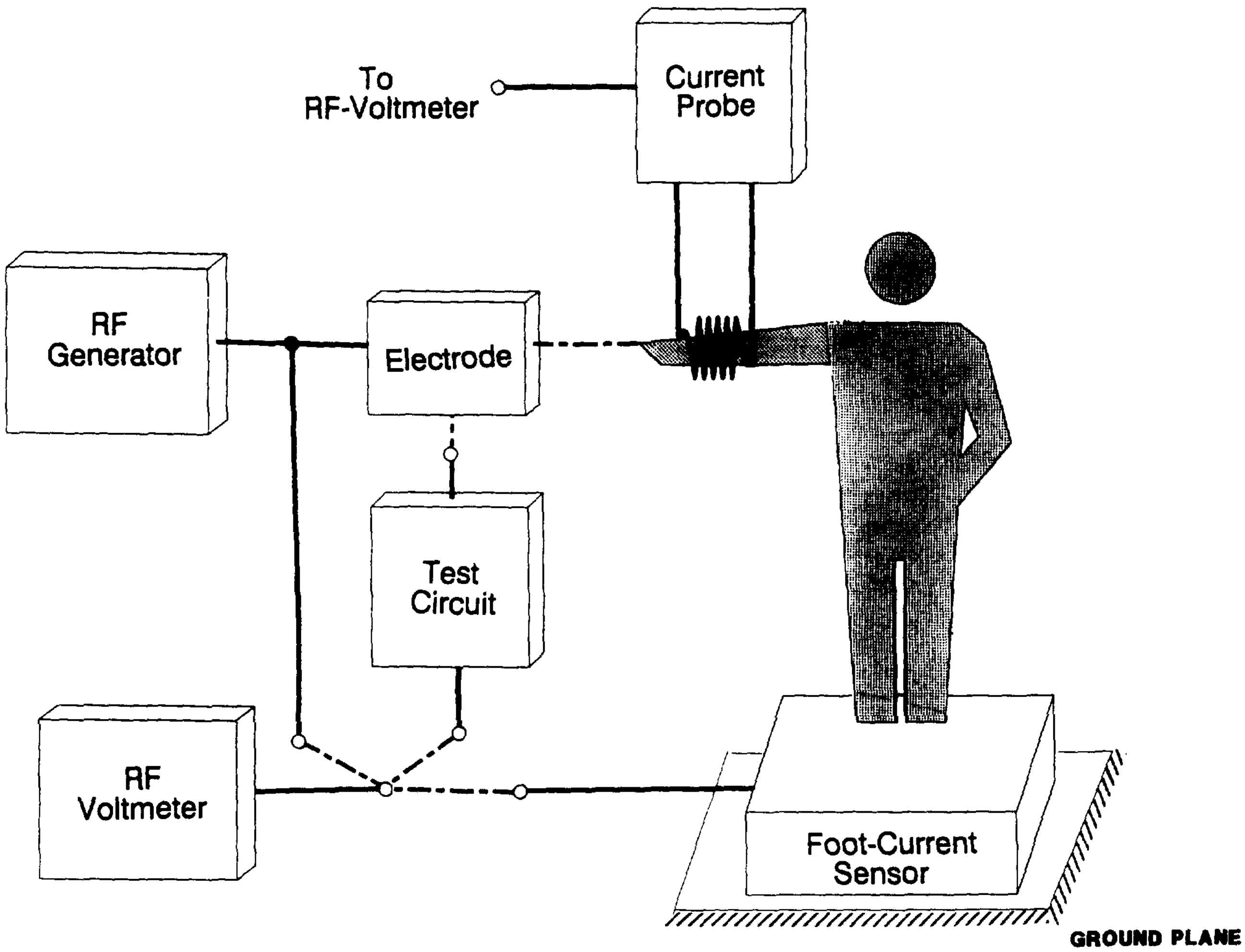


Fig. 5. Schematic diagram of the experimental arrangement for measurements of currents through the test circuit, and finger and feet of a test subject (human).

Field tests

Field tests were performed at transmitter sites operating at 7.3 MHz and 18 V m^{-1}, and 162 kHz and 7 V m^{-1} with a Chevrolet Cavalier wagon as a test object. No sites of sufficient field strengths were available at higher frequencies. The test circuit was connected between the door handle of the car and a 1-m^2 copper plate placed on the ground. Voltage at the output terminal of the test circuit was measured with an RF voltmeter. Current through the finger of a person was also measured using a current probe. Measurements were performed for the barefooted person standing on the copper plate or directly on grass. The results of these measurements are summarized in Table 4.

DISCUSSION

It is apparent from the measurements of the body impedance circuit (Fig. 10) and the foot-current sensors (Figs. 7 and 8) that construction and layout of the circuits' components critically affects their impedance at frequencies higher than approximately 10 MHz. It is also apparent from the measurements of the foot current vs. finger current (Fig. 11) that the stray capacitance of the body reduces the current (in this case foot current) significantly at high frequencies in the tens of megahertz range. A similar effect is expected from the stray capacitance of an object.

The contact current through a person touching an object is related to the short-circuit current of the object by the following equation:

$$I = I_o \frac{\dfrac{-j}{\omega C_o}}{\hat{Z} - \dfrac{j}{\omega C_o}}, \qquad (5)$$

where I_o is the object short-circuit current, C_o is the object capacitance to ground (stray capacitance), and $\hat{Z}$ is the impedance of the human body. The capacitance C_o ranges from about 800 pF for an average car to approximately 2000 pF for a school bus and 3000 pF for a truck (Guy

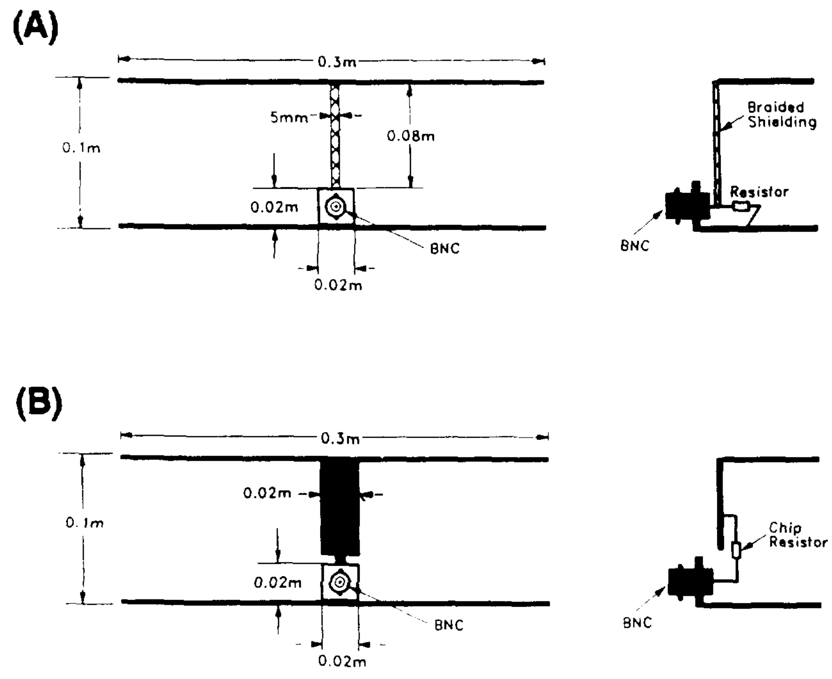


Fig. 6. Construction of foot-current sensors "A" and "B."

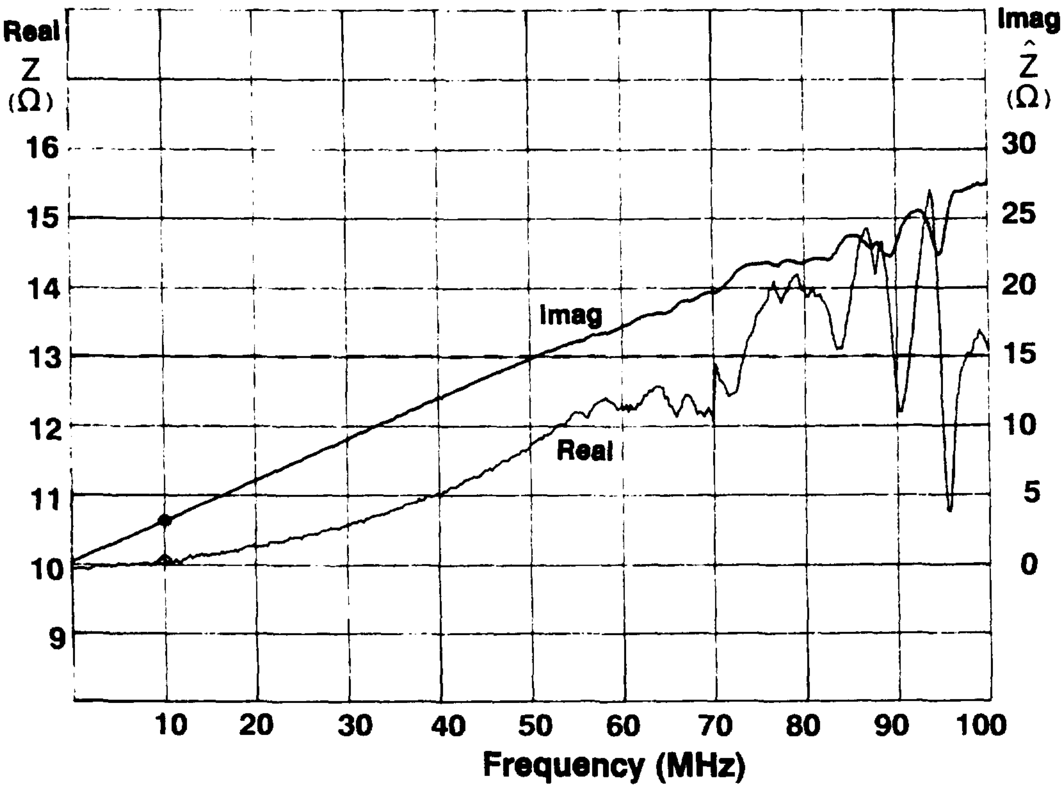


Fig. 7. Impedance of the foot-current sensor, model A.

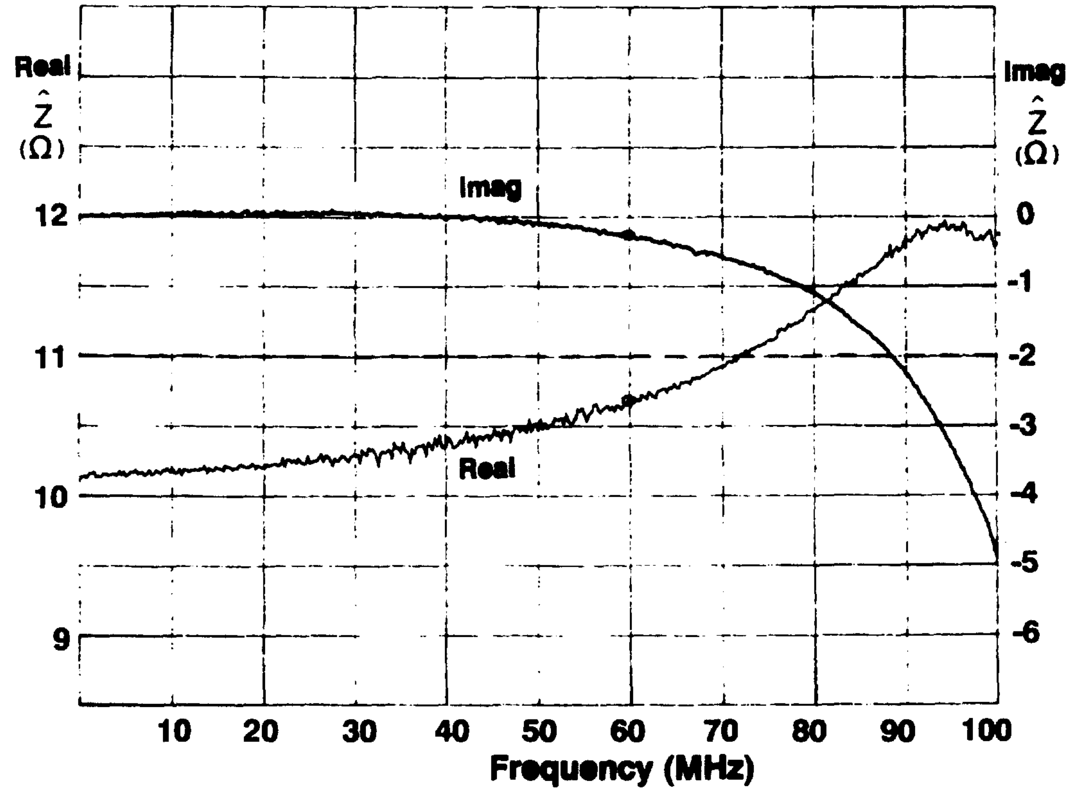


Fig. 8. Impedance of the foot-current sensor, model B.

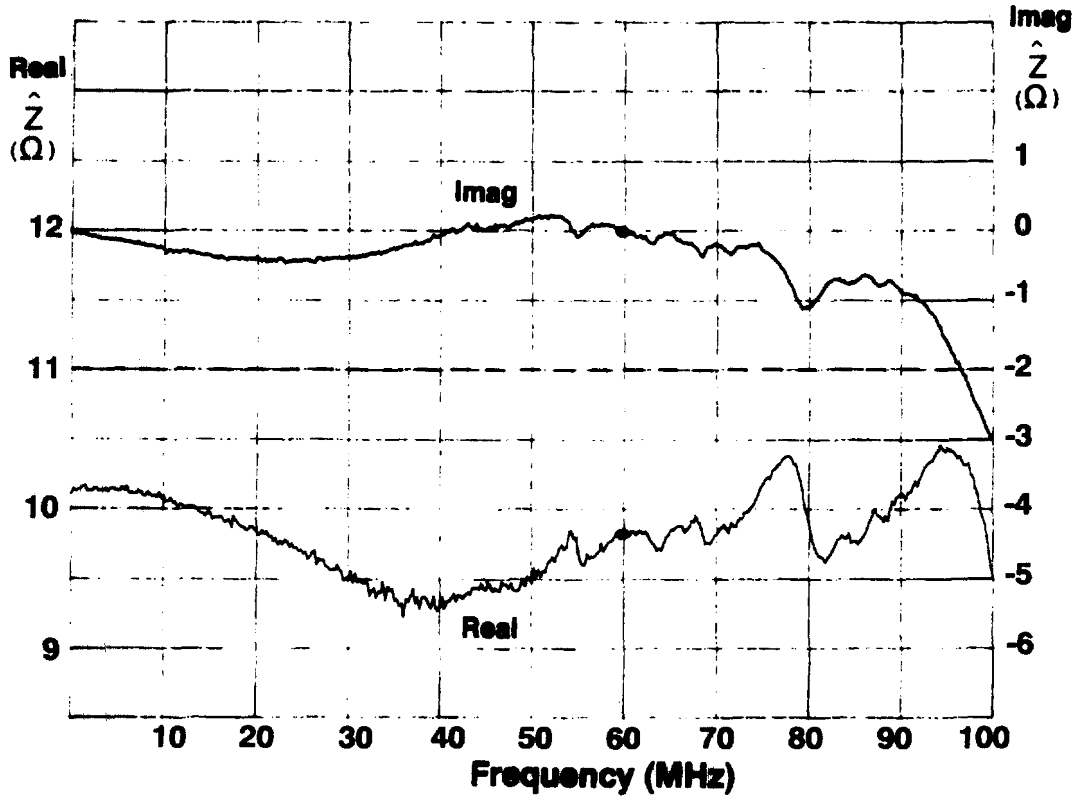


Fig. 9. Impedance of the foot-current sensor, model B, with a person standing on the upper plate of the sensor (not touching any object).

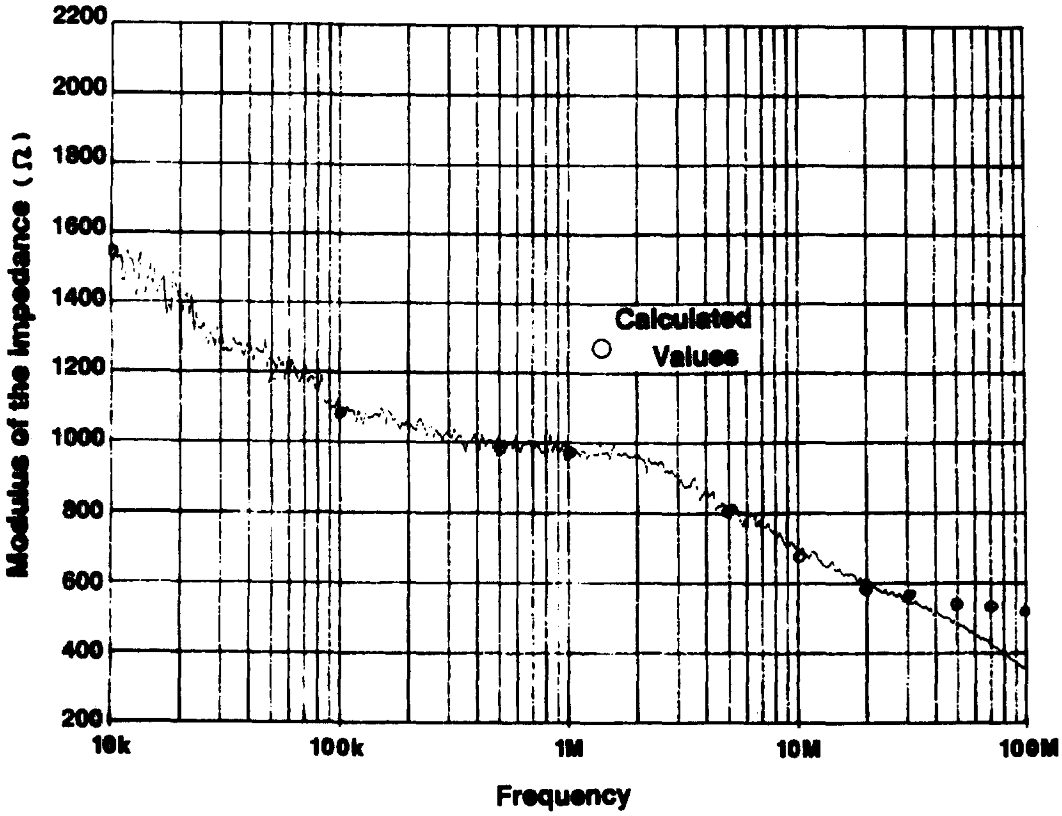


Fig. 10. Measured and calculated impedance of the test circuit representing the human body for finger contact and barefeet.

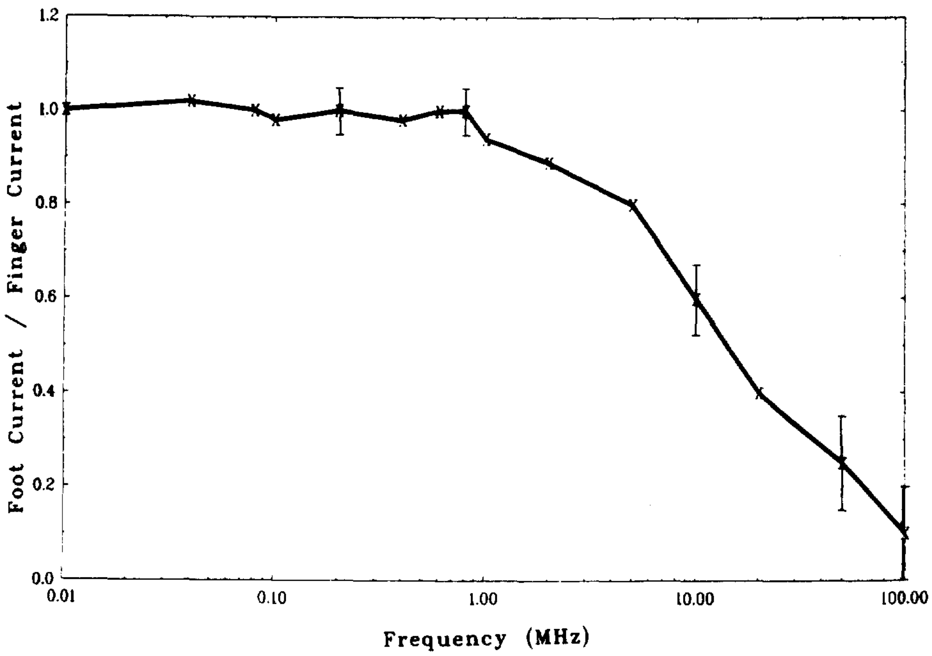


Fig. 11. Ratio of foot current to finger current as a function of frequency. Vertical bars show the estimated uncertainty in measurements.